Palaeomagnetism and Ore Deposits

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Abstract

The ways by which rocks acquire a magnetisation can be used to distinguish the thermochemical history of ore deposits and offers a tool for both relative and absolute dating. In addition, "standard" palaeomagnetic techniques can be used to determine the structural development of the area in relationship to neighbouring regions, as well as assisting in determining the internal evolution of an ore deposit.

Zusammenfassung

„Paläomagnetismus und Erzlagerstätten"

Das Vorkommen von Erzlagerstätten in Zusammenhang mit Bewegungen von Kontinenten (oder Platten) muß von zwei Gesichtspunkten betrachtet werden. Der einfachste Fall ist dort gegeben, wo bestehende Lagerstättenprovinzen aufgespalten und die Teile in verschiedenen Kontinenten separiert werden wie z. B. die Nickellagerstätten von Australien — Antarktis — Indien — Afrika oder die Diamantenfelder von Westafrika und Guyana. Der kompliziertere, aber häufigere Fall ist der, daß beim Aufbrechen der Kontinente Bedingungen geschaffen werden, unter welchen Erze infolge eindringender magmatischer Lösungen entlang der Plattenränder angereichert werden. Beispiele hiefür sind die Blei-Zink-Silber-Lagerstätten von Irland und Norwegen oder das Rote Meer. Paläomagnetische Untersuchungen sind hier, indem sie die ursprüngliche Lage der Kontinente bestimmen, von entscheidender Bedeutung. Das gilt vor allem auch für Lagerstätten, die weitgehend von den palöoklimatischen Bedingungen abhängig sind, wie z. B. Bauxit-, Gips- und möglicherweise auch Erdöl- und Erdgas-Lagerstätten.

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Für die letzten 75 Millionen Jahre sind die paläomagnetischen Messungen des Ozeanbodens die genaueste Methode, um frühere Lagen der Kontinente zueinander zu erfassen. Diese Methode kann höchstens bis in den Jura oder vielleicht bis in die Trias ausgedehnt werden, wenn eine genauere Datierung der inversen Folge im Mesozoikum möglich ist. Für die Zeit des Mesozoikums und jedenfalls für die älteren Zeitepochen sind die paläomagnetischen Messungen an kontinentalen Gesteinen für die Bestimmung der Lagen der Kontinente und somit auch für die Festlegung des Beginns des Auseinanderbrechens von Kontinenten oder des Zeitpunktes von Kollisionen zwischen Teilen von Kontinenten von entscheidender Bedeutung.

Die Genauigkeit solcher Rekonstruktionen ist zur Zeit noch viel stärker von der Verläßlichkeit der Ausgangsdaten als von den theoretischen Grundlagen der paläomagnetischen Methode abhängig. Dennoch besteht die Möglichkeit, Hoffnungsgebiete für Erzlagerstätten anzuzeigen.

1. *Introduction*

Palaeomagnetic studies of continental and oceanic rocks (*Irving*, 1964; *Tarling*, 1971; *McElhinny*, 1972) have played a crucial role in recent changes in the concept of continental drift, and clearly palaeogeographic reconstructions based on these concepts are likely to be of some value in relating ore deposits within and between continents. More significantly, ore minerals may either consist of ferromagnetic minerals, such as heamatite and magnetite, or contain them in significant quantities as accessory minerals. Thus a study of the origin of the magnetisation of these minerals can, in many cases, be used to investigate the physical condition under which the ores were deposited and, if geomagnetic field changes are resonably well documented for other rocks in the region, it should be possible to obtain relative or absolute dates for the ore deposits by direct comparison of their direction of remanence with those of rocks of known ages. Similarly, the application of palaeomagnetic techniques may yield information on the gross tectonic evolution of the ore field or assist in petrofabric analyses where standard techniques appear to be less effective.

This article is mainly concerned with the way in which rocks acquire their magnetisation (Section 2) and how this can be used for the dating of ore bodies (Section 3). Palaeolatitude, tectonic and petrofabric considerations are only considered briefly in section 4.

2. *The Acquisition of Remanent Magnetisation*

The ways in which rocks acquire a remanent magnetisation are now fairly well known although it may be difficult to assess the major factors involved in any one particular example, particularly in the case of ore deposits. Essentially two main physical processes are involved. As an igneous rock cools from its molten state, it solidifies and eventually passes through the Curie temperature of its component magnetic mineral. This temperature, mostly below 680^{0} C in rocks, is where the quantum mechanical forces between iron atoms become sufficient to couple their electron spins so that they are brought into alignment with any external field, despite the disrupting action of thermal vibrations. The length of time during which this alignment is maintained is the *relaxation time;* the time it takes for the direction of remanent magnetisation to change from its original direction to that of a newly applied field, or to become randomly oriented in the absence of an external field. The relaxation time (τ) of a magnetic grain is dependent on its composition (K) and also on its volume (V) and temperature (T) — $\tau \alpha K (V/T)^{1/2}$ — i. e. below its Curie temperature its relaxation time increases approximately exponentially for a linear increase in volume or decrease in temperature (Néel 1955). An increase in volume or decrease in temperature can therefore result in the preservation of a direction of remanence throughout geological time; the temperature or volume at which the grain acquires a relaxation time of the order of a few minutes is termed the ”blocking“ temperature or ”blocking“ volume i. e. when the relaxation time corresponds to the duration of normal laboratory experiments. Large particles (haematite greater than 10^{-3} cm diameter, titanomagnetite greater than abouth 10^{-5} cm diameter) also develop strong magnetostatic forces because of the separation of magnetic poles on opposite ends of the grain. These cause the atomic alignments within the grain to form antiparallel groupings (domains) and such multidomain particles can change their net direction of magnetisation by unrolling the ”wall“ between each domain, so such large particles are generally less magnetically stable than single domain particles. As atoms within grains are able to migrate, especially at high temperatures ($> 600^{0}$ C), this allows the exsolution of the individual large titanomagnetite grains into lamellae of, for example, ulvospinel and magnetite or ilmenite and haematite. The individual magnetite or haematite exsolutions may be of single domain size, physically isolated from each other by a non-magnetic matrix and thus magnetically very stable, although the original particle was large.

As an igneous rock cools, a stable remanence is acquired by the single domain particles, in particular, so that when these particles are eroded and subsequently deposited as a wet slurry, they become physically aligned along the Earth's mangetic field direction. Subsequent cementation may preserve this direction, but the diagenesis is also associated with major chemical changes in magnetic minerals, particularly the dehydration of clay minerals, goethite, etc., to form haematite, and the oxidation of other iron-bearing minerals (olivines, pyroxenes, amphiboles, etc.) As the haematite or magnetite grows, individual grains acquire a remanence directed along the ambient magnetic field as they pass through the blocking volume and, if growth continues, this direction may be preserved indefinitely. Sedimentary rocks are therefore likely to carry a remanence associated with both deposition and diagenesis, so that the age of the stable remanence is normally only that of the age of formation the rock if diagenesis took place shortly after deposition.

Many rocks may therefore contain ferromagnetic particles which carry a remanence acquired when the rock originally formed, but the wide range of grain sizes usually means that a wide spectrum of relaxation times is present. Grains of low relaxation time will have lost their original direction, but will also have acquired a magnetisation in later magnetic fields. However, the magnetisation of such short relaxation time grains can be preferentially removed if rock samples are subjected to partial demagnetisation by incremental temperatures or alternating magnetic fields. Incremental demagnetisation can therefore isolate the remanence associated with grains of long relaxation times in many rocks. However, this critical size range may be absent or consist of such a small component of the total magnetic fraction that instrumental defects (such as a few gammas direct field while cooling during thermal demagnetisation or even harmonies in the current producing the alternating magnetic field) may mask any high stability component. This has meant that most standard palaeomagnetic work has hitherto been mainly concerned with basic to intermediate igneous rocks and red siltstones, but technical improvements in both measurement and demagnetisation is allowing a wider range of rock types to be used in palaeomagnetic studies. Comparatively few studies have so far been undertaken on either metamorphic rocks or ore bodies (although some particular examples are mentioned below). This arises because the origin of remanence in such rocks is likely to be complex and also the direction of remanence which was acquired may not exactly parallel the ambient field because the magnetic particles carrying the remanence are likely to be inhomogeneously distributed within the rock samples and there may be a net alignment of either the crystallographic axes or grain shapes which causes the direction of remanence to be pulled towards an "easy" directions of magnetisation, i. e. along the [111] axis of aligned magnetites or the net major axis of elongate particles. These anisotropic effects can be used in magnetic structural analyses (Section 4). An elongation of macroscopic or microscopic grains may not necessarily apply to the submicroscopic domain size particles which carry the most stable remanence and there is evidence that anisotropic effects are reduced by partial demagnetisation. Nonetheless in the initial development of palaeomagnetic studies, samples of rocks in which the anisotropy was in excess of 5 % (max. susceptibility/min. susceptibility greater than 1.05) were generally ommitted from further study (*Irving* 1964).

In the case of metamorphic rocks and ore deposits, heamatite and magnetite are common accessory minerals but the processes of magnetisation must involve varying degrees of thermal heating and crystal growth, often while the rocks are under pressure. The main effect of pressure appears to be the creation of directions of preferred crystal growth which enhance anisotropic properties, but direct magnetic effects are mostly lost when the pressure in removed. The slow cooling and prolonged crystal growth in many ore bodies means that the total remanence for a single ore sample may have been acquired over a prolonged period and therefore reflects the average of possibly complex geomagnetic field changes. Nonetheless, it is becoming increasingly clear that the palaeomagnetic study of ore minerals, and their associated rocks, should yield information on the processes and rate of ore accumulation.

3. Palaeomagnetic Dating

As magnetically isotropic rocks acquire a magnetisation parallel to the geomagnetic field at the time they pass through their blocking temperature or blocking volume, it is possible to use changes in the direction, and, to a lesser extent, the strength of the geomagnetic field as a means of dating this event. The Earth's magnetic field shows an extremely wide spectrum of changes, from microsecond pulsations to polarity reversals and polar shifts over 10^7 years and greater. In general most metallic ore bodies take at least a 1000 years to form so that all changes of less than 1000 year periodicity are likely to be averaged out. Therefore dating by comparison with short term secular changes, which is applicable in archaeological studies, is not likely to be relevant, except under exceptional circumstances. Studies of such changes, however, indicate that on longer time scales, these secular changes average out to yield an average geomagnetic field which is very close to that of a single axial geocentric dipole and this concept (discussed further in Section 4) is assumed to be valid for most of geological time. This means that it is possible to allow for the spatial variation in the geomagnetic field by defining the palaeomagnetic direction in terms of the corresponding pole position. (This is, in fact, merely another mathematical way of describing the direction of remanence and it is a different philosophical step to attribute this pole position to an actual geomagnetic pole. Over a small region, a few hundred km^2, the spatial variation of the geomagnetic field is small and palaeomagnetic directions can be compared directly.) With increasing geological time, the average pole positions for each stable tectonic block become increasingly displaced from the present rotational pole, forming a polar wandering curve (Figure 1), but each tectonic block has its own distinct curve so that, for example, the polar wandering curves of the last 300 million years for Europe and North America, derived from rocks unaffected by orogenic activity, follow a similar pattern, but only begin to converge during the last 180 million years. Many palaeo-continental reconstructions, of course, depend on matching such polar wandering curves. When such curves are available, it is possible to obtain average directions for rocks of unknown age on the same block and, by comparison with the established polar wandering curve, the time at which they acquired their remanence can be determined — an example in relation to ore bodies is given by *Hanuš & Krš* (1963). Where such curves have not been established, it is still

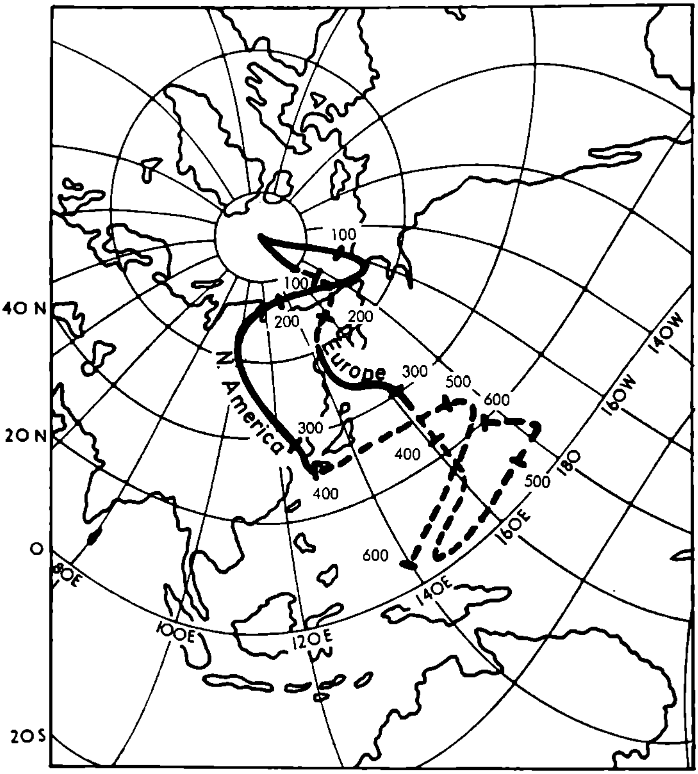

Fig. 1. Polar Wandering Curves of Europe and North America. The solid lines indicate well documented pole determinations, and broken lines indicate where there is still uncertainty about the precise pole positions.

possible to obtain the relative ages of different rocks by comparison of their directions. The injection of dykes in some parts of the Canadian Shield, for example, appears to have been approximately contemporaneous as most of the dykes have a very similar direction of remanence, so that there cannot have been much movement between the shield and pole during the time the dykes were injected (*Larochelle,* 1967). Conversely studies of haematite bodies in the Lake Superior region have shown that some ore bodies have directions similar to intrusive rocks and are therefore probably syngenetic, while others have significantly different directions and are therefore probably residual weathering products (*Symons,* 1967 a, b).

The accuracy of this method of absolute dating is very difficult to evaluate as precise polar wandering curves have not yet been satisfactory established for most continents, and the precision will also depend on the rate at which the sampled area and pole are moving relative to each other. Nonetheless, it seems likely that an accuracy of some 10^7 years can be achieved by this method if at least 50 separately oriented samples with stable remanence, can be collected for a time of relative polar movement of some 0.5^0/m. y. (the average relative polar movement is 0.3^0/m. y. for Europe during the Mesozoic-Cenozoic).

More precise dating is possible using reversals of the polarity of the geomagnetic field. These were first identified at the start of this century, but detailed study of the age sequence of polarity changes has only been achieved during the last decade. These have shown that the reversals take place irregularly, although possibly statistically conforming to a Markov chain sequence *(Parks,* 1972). The events during an actual transition of polarity are only poorly known, but it appears that there is a decrease in intensity of the geomagnetic field over a period of some 4000 years, when it falls to approximately on fifth of its usual value. The actual polarity change then takes place over an interval, possibly as short as 2000 years, and is followed by a gradual return to its usual intensity over another 4000 years. This polarity is then retained for 10^4 to 10^7 years. The polarity transition is, therefore, geologically instantaneous and world-wide and forms an ideal dating horizon. Further study may show that the precise nature of each reversal may be sufficiently different that detailed studies may allow their specific identification, but this is unlikely to be applicable for some decades, if at all, and is probably of too short a duration to be isolated during the formation of ore bodies. Nonetheless it is possible to match polarity sequences or, if the approximate age is already known, the presence of reversals may allow more precise dating than either normal palaeontological or radiometric methods. One particular example is the magnetisation acquired by deep-sea manganese nodules which have recently been shown to contain both normal and reverse polarities *(Crecelius, Carpenter* & *Merrill,* 1973). The normal polarity was acquired during the last 700,000 years, i. e. during the present normal polarity period, and the reversed components are older, confirming the very slow rate of growth of these mineral deposits. Similar dating, with very high precision, is possible through most of the Cenozoic as the polarity sequence is well documented from oceanic magnetic anomaly patterns *(Heirtzler* & al., 1968; *Tarling,* 1971) and fuller information is gradually becoming available for much of the late Palaeozoic and Mesozoic (Figure 2). It is known that the Earth's magnetic field was almost entirely of reversed polarity in the late Carboniferous and for most of the Permian (280 to 230 m. y.) but was equally normal and reverse during most of the Triassic (190—230 m. y.), and mostly normal during the Jurassic and Cretaceous. Thus it is possible to distinguish between Permian and Triassic sandstones, or ore bodies, using the ratio of normal to reversed rocks as long as a several million year interval is sampled.

It is known that certain minerals of specific composition have the ability to self-reverse, i. e. on cooling they acquire a direction of remanence in opposition to that of the ambient field. Similarly, intra-crystalline re-arrangements over

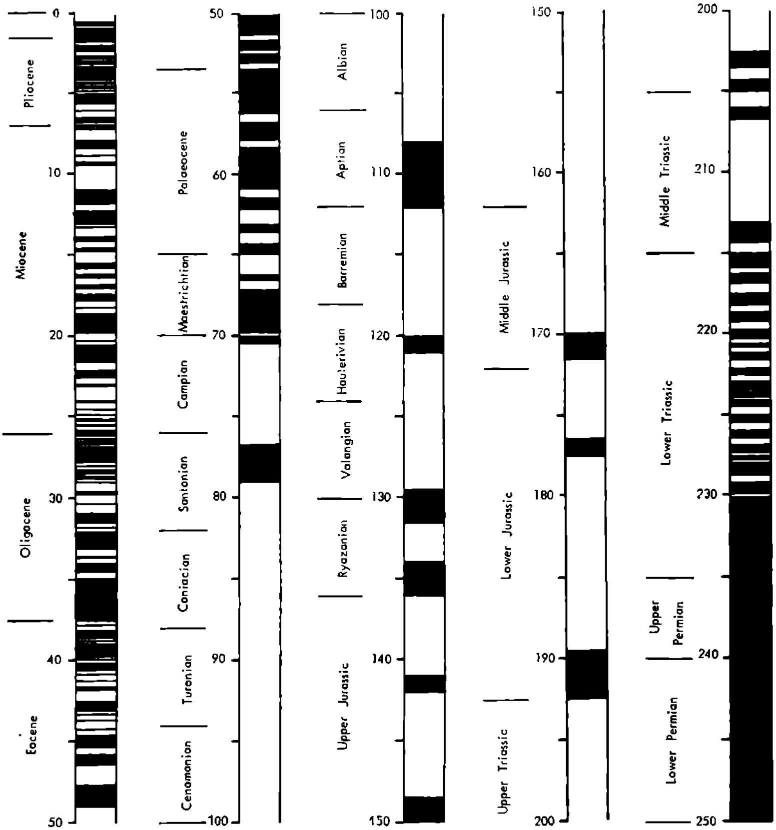

Fig. 2. The Mesozoic-Cenozoic Polarity Sequence. The white bands correspond to present day "normal" polarity and the black correspond to "reversed" polarity zones. The Cenozoic scale is estimated to be accurate within some 3 %, but the detailed timing of Mesozoic polarity changes is subject to greater modifications as further polarity changes are documented, but mainly as dating techniques and data are improved.

geological time may cause the magnetic polarity of the sample to reverse. However, these processes are now fairly well understood *(Ishikawa & Syono,* 1963) and are restricted to rare and specific mineral compositions under abnormal physical conditions. Thus it is extremely unlikely that such self-reversals will be encountered and only one well authenticated naturally self-reversing rock is known, the Haruna dacite of Japan *(Nagata, Uyeda & Akimoto,* 1952) despite the many thousands of rocks which have been examined for this property.

4. Geotectonic and Palaeolatitude Applications

Rocks which acquired their remanence at the same time, have not moved relative to each other subsequently, and carry a stable remanence, must have directions of magnetisation which reflect the original geomagnetic field. Studies of archaeological material, lake and glacial sediments deposited during the last 10,000 years, deep-sea sediments magnetised during the last 3 m. y., lavas and dykes formed during the last 20 m. y. all show individual directions which correspond to pole positions scattered around, but strongly centred upon the Earth's present axis of rotation. These numerous observations therefore confirm theoretical considerations for an axial geocentric model of the average geomagnetic field. However, individual studies of igneous rocks have also shown that during some of this time, the Earh's average field may be more closely described by an axial dipole that is displaced northwards by some 200—300 km from the Earth's centre, thereby causing the poles of individual collections to consistently lie some 4^0 on the far side of the pole *(Wilson,* 1970, 1971). This raises some problems about the precise nature of the geomagnetic field and whether this effect is in fact a reflection of other tectonic processes rather than invalidating the axial geocentric dipole model. Nonetheless, for most palaeogeographic reconstructions, this discrepancy is small and is within the statistical limits of almost all average pole determinations. For earlier times, the movement of different tectonic blocks during continental drift, etc., means that global comparisons cannot be made using the present distribution of the continents, but the available palaeomagnetic data remains consistent with a geocentric dipole model on a continental scale. An agreement with such generally accepted palaeoclimatic indicators as coral reefs, archaeocyathids, dolomites, red beds, evaporites, etc., suggests that this dipole is also axial. Unfortunately these palaeoclimatic indicators can only be used as a rough guide as they are sensitive to local geographical factors, global varations in climate, etc. (Conversely, palaeoclimatic conditions should not be inferred precisely from precise palaeomagnetic determinations of palaeolatitude determined using the formula, tan (palaeolatitude = $^{1}/_{2}$ than [inclination of remanence]). Nonetheless, it is clear that the axial geocentric dipole model for the average geomagnetic field is a very close first approximation for most of geological time, with the noteable, but brief exceptions of intervals of polarity transitions. It is therefore possible to make first order geological interpretations of palaeomagnetic observations in this way.

In terms of ore deposits, this means that approaching continents must be separated by an ocean which includes an active subduction zone with its associated ore deposits *(Guild,* this issue; *Mitchell & Garson* 1972; *Sawkins,* 1972). Past subduction and collison zones can therefore be documented from palaeomagnetic studies. Similarly, parts of oceanic crust and mantle may become incorporated into continental rocks during continental closures, affording potential ore sources from already differentiated and deposited minerals, such as the copper ores of

Cyprus, Turkey, etc., as well as rocks which, when subjected to chemical weathering, etc., may develop localised enrichments, such as the nickel and chrome deposits of New Caledonia. Ores may also be transported into stable continental areas in which palaeoclimatic considerations may be of major significance in creating optimum environments for their deposition and concentration *(Tarling* 1973). Naturally, similar palaeoclimatic considerations apply even more directly where deposits of evaporites, phosphates, etc. are involved. These factors are clearly more significant than simple jig-saw considerations of continental drift, such as the prediction of ore deposits in Antarctica from those mapped in Australia, or gold and diamonds in Africa matching those in South America etc.

On a more localised scale, the same techniques can be applied to unravel the tectonic developments within individual continental blocks, so that, for example, the relative movements between extra Alpine Europe and the Iberian peninsula, Corsica-Sardinia, etc., are becoming better documented following palaeomagnetic studies and these "local" tectonic events have a clear significance in understanding, for example, the origin for the mineralisation in Sardinia and Tuscany. Local tectonic interpretations, based on palaeomagnetic studies, have also been made to determine, for example, if the Sudbury nickel deposits were laid down in approximately their present position, or were originally quasi-horizontal and have subsequently been folded *(Hood* 1961), and there are numerous similar structural problems to which palaeomagnetic techniques may afford both direct and indirect information. As both haematite and magnetite are stress sensitive minerals, it is also possible that current studies of the detailed magnetic structure of rock samples may quickly and simply yield petrofabric information relevant to past stress fields which is not discernable from standard petrofabric analyses of the orientation quartz grains, micas, etc.

5. Summary

An increased understanding of the processes by which rocks acquire their magnetisation now means that the study of the remanent magnetisation associated with ore bodies may yield major clues about the processes of formation of the ores. The directions of remanence of the ores and associated rocks may also be used for dating purpose or for deciphering the tectonic evolution of the region on both a large and small scale. The number of palaeomagnetic observations which have been made on ore bodies is, so far, few, but it is clear that there is a considerable potential in applying palaeomagnetic techniques to a variety of problems associated with the genesis and evolution of ore bodies.

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